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PERFORMANCE ANALYSIS OF A WINDOWED HIGH TEMPERATURE GAS RECEIVER USING A SUSPENSION OF ULTRAFINE CARBON PARTICLES AS THE ABSORBER

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ABSTRACT

This paper summarizes the results of an analytical study of the efficiency of single and double-windowed high temperature solar receivers suitable for use with small central tower or point focus dish collectors. A detailed window energy balance is used to predict the window temperature. The receiver energy losses, receiver efficiency, and associated thermodynamic cycle efficiency are calculated. The efficiencies for the base line design for single and double-windowed receivers are 93.8% and 95.4% respectively. A sensitivity analysis is used to determine the effects of varying the temperature, concentration ratio and glass reflectivity.

1. INTRODUCTION

Recently, there has been renewed interest in windowed high temperature receivers for solar thermal applications. The Small Particle Heat Exchange Receiver (SPHER) concept utilizes a windowed receiver to confine a suspension of ultrafine carbon particles that act as the solar absorber and heat exchanger(1). This and other receivers have been proposed to heat a gas to a high temperature for powering a gas turbine or to supply industrial process heat. Other applications of windowed receivers include their use to confine suspensions of feedstock materials during solar heating.

In view of these applications of high temperature windowed receivers, an analysis was performed to determine the overall efficiency of two specific receiver designs. The designs were intended for use with the SPHER concept, but the methodology that was developed [described in more detail elsewhere(2)] is applicable with only slight modification to a wide variety of windowed receiver designs and sizes.

Two basic designs were analyzed. One used a single window with a hot working gas flowing behind it. The second design used two windows with a cooling gas flowing between them. Both designs were assumed to be used in conjunction with a regenerated gas turbine system providing several megawatts of mechanical power. An efficiency analysis was first performed for a baseline design. Then a sensitivity analysis was performed by changing the value of each parameter to determine its effect on the receiver efficiency. The results are presented in the form of tables and graphs.

2. THE WINDOW

The window may perform several functions depending on the receiver design and the thermodynamic requirements of the associated system. It may be used to prevent mixing between the receiver working fluid and the ambient air. If the receiver is pressurized, it must form part of the pressure vessel. The window will reduce energy losses by trapping the thermal radiation emitted from inside the receiver thereby significantly increasing the overall efficiency.

The window should have high thermal stress- and shock-resistance, and be capable of operating at high temperatures. Desirable optical properties include a high solar transmittance, and a low transmittance to radiation emitted by the cavity.

Three acceptable window materials were identified in the study. They are Corning Vycor Glass (Code No. 7913), Corning Fused Silica (Code No. 7940), and a Corning Titanium Silicate (Code No. 7971). These window materials are high purity silicate glasses with continuous maximum operating temperatures of $1170^{o}K$, $1170^{o}K$, and $1070^{o}K$ respectively. Glass No. 7971 is a titanium doped fused silica with an extremely low coefficient of thermal expansion

Selective etching techniques can be used to reduce glass reflectivity (as distinct from an anti reflection coating). This process will reduce the solar reflectivity of borosilicate glass (Corning 7740) to 0.25% per surface over the solar spectrum(3). The etching process produces a continuous gradient in the index of refraction at the glass surface. A survey of the technology indicated that it is possible to produce a Fused Silica Glass (such as 7940) with low reflectivity using a technique similar to that used with the 7740 glass. With this in mind, baseline calculations have been performed with a reflectivity value of 0.5% per window.

In the base line design, the window has the form of a shallow spherical cap that is convex towards the pressure region. This design, when supported properly, is much stronger than a flat window because the glass is held in compression. A discussion of the strength, stresses, buckling, and sealing of spherical dome windows is included in Ref. 2.

3. BASIC ASSUMPTIONS

The base line receiver was assumed to have an circular opening 1.67 meters in diameter, and a window thickness of 2 cm. For the baseline design the concentration ratio is 2000 and the receiver collects about 4 Mw of thermal energy. The pressure ratio for the thermodynamic cycle was optimized to a value of four with an output air temperature from the receiver of $1273^{\circ}K$. The basic assumptions in the analysis are listed below. In general the assumptions that are made are conservative, (ie. tending to over-estimate the receiver energy losses).

a. The cavity is assumed to be a uniform black body emitter at the maximum cavity temperature.

b. It is assumed that a gas at the cavity temperature transfers heat by convection to the inner surface of the window.

c. The backscattered loss of solar energy from the cavity is assumed negligible (this applies better to the SPHER concept than other receivers due to the very high absorption of the small particles). If the solar flux scattered out of the receiver is small, it may be considered independently of the other losses.

d. The window temperature is assumed to be uniform both parallel and perpendicular to the window surface. As a check on this assumption, calculations based on a three layer model for the window were performed, taking account of both the radiative and conductive exchange between the layers. They yielded a temperature gradient of approximately $130^{\circ}C$ across the window thickness in the single window receiver. This gradient effects the receiver efficiency by only 0.2% in the baseline case.

e. The incident solar flux is assumed to be uniform.

In the double window receiver design, active window cooling is provided. The window cooling air comes from the compressor of a gas turbine and passes on to the regenerator. The windows are assumed to be concentric spherical shells separated by 12.4 cm and made from Corning Vycor Glass (Code No. 7913).

4. ANALYSIS OF A ONE WINDOW RECEIVER

The window temperature is calculated in a window energy balance. The window absorbs a portion of the radiant energy emitted by the cavity. It also absorbs a small fraction of the incident solar energy. Heat is convected to the inner surface of the window from the receiver working fluid. The window loses energy by radiant emission and by the forced and free convection from its outer surface to ambient air.

In steady state conditions, the sum of heat losses from the window must equal the sum of heat inputs to the window. If each of the heat flux terms is identified and expanded, the following equation results:

$$\alpha(T_c)\sigma T_c^4 + \alpha_s I_s + h_{c,i}(T_c - T_g) - 2\hat{\xi}(T_g)\sigma T_g^4 - h_{c,o}(T_g - T_\infty) = 0, \tag{1}$$

where σ is the Stefan-Boltzmann constant, $\alpha(T_c)$ is the window absorbance for black body radiation at a temperature T_c, and the other terms are identified in Table I. This treatment assumes that the area of the window is approximately equal to that of the opening. Accurate values for the window optical properties are necessary because they have a large effect on receiver efficiency. They were determined by a numerical integration process using data from a spectral transmission curve supplied by the manufacturer and an associated tabulation of indices of refraction. Air mass 1 data was used for the solar spectrum.

The methods used to calculate the convective heat transfer coefficients ($h_{c,i}$ and $h_{c,o}$) at the window inner and outer surface, are described in Ref. 2. Reasonable variations in either of these coefficients has a relatively small effect on the receiver efficiency.

The receiver collection efficiency, η, is defined as unity minus the ratio of total energy lost from the receiver to the incident solar flux. For the one window case, the receiver collection efficiency is:

$$\eta_s = 1 - [\tau(T_c)\sigma T_c^4 + \rho I_s + \xi(T_g)\sigma T_g^4 + h_{c,o}(T_g - T_\infty)]/I_s. \quad (2)$$

Table I

Base line results - One window system

Quantity	name	value
α_s	Absorbance	0.011
$\tau(T_c)$	IR Transmittance	0.305
T_∞	Ambient T	298°K
$\alpha(T_c)$	IR Absorbance	0.685
ρ	Reflectivity	0.005
T_c	Cavity Temp.	1273°K
I_s	Incident flux	2×10^6 w/m^2
$h_{c,i}$	Inner Conv. Coef.	11.0 w/m^2 °K
$h_{c,o}$	Outer Conv. Coef.	11.4 w/m^2 °K
T_g	Glass Temp.	1070°K
$\xi(T_g)$	Window Emittance	0.775
η_s	Efficiency	.938

5. ANALYSIS OF A TWO WINDOW RECEIVER

To predict the window temperatures in the double window receiver, the simultaneous solution of two window energy balance equations and an energy balance equation for the window cooling air is required. The energy balance for the inner window (window 1) is given by:

$$\alpha(T_c)\sigma T_c^4 + \tau_s\alpha_s I_s + F_{12}\alpha(T_2)\xi(T_2)\sigma T_2^4 + h_{c,i}(T_c - T_1) + F_{12}[(\tau\alpha)(T_c)\sigma T_c^4 + \xi(T_1)\alpha(T_1)\sigma T_1^4]\rho = 2\xi(T_1)\sigma T_1^4 + h_{c,1}(T_1 - T_a), \quad (3)$$

where T_a is the average temperature of the window cooling air, and $F_{1,2}$ is the radiative shape factor between window one and window two ($F_{1,2}$ is very close to unity for this design). Similarly, the outer window (window 2) energy balance is:

$$(\tau\alpha)(T_c)\sigma T_c^4 + F_{21}\alpha(T_1)\xi(T_1)\sigma T_1^4 + \alpha_s I_s + F_{21}[(\tau\alpha)_s I_s + \xi(T_2)\alpha(T_2)\sigma T_2^4]\rho = h_{c,o}(T_2 - T_\infty) + 2\xi(T_2)\sigma T_2^4 + h_{c,2}(T_2 - T_a). \quad (4)$$

The symbols in Equations 3 and 4 are identified in Table III. The equation for the cooling air energy balance and the convective cooling coeficients are treated elsewhere(2).

The efficiency of the two window receiver is defined in the same manner as for the one window receiver. The resulting equation for the receiver efficiency is:

$$\eta_D = 1 - [\tau_{1,2}(T_c)\sigma T_c^4 + \xi_1(T_1)\tau(T_1)\sigma T_1^4 + \xi_2(T_2)\sigma T_2^4 + \rho_{eff} I_s + h_{c,o}(T_2 - T_\infty)]/I_s, \quad (5)$$

where ρ_{eff} is the effective reflectivity for a two window system.

6. THERMODYNAMIC CYCLE

The receiver is assumed to take the place of the heat source in an open cycle, regenerated gas turbine, as illustrated in Figure 1. The flow is through path (a) for the single window and path (b) for the double window case. The thermodynamic cycle efficiency is calculated assuming a regenerator efficiency of 0.8, a turbine efficiency of 0.9, a compressor efficiency of 0.8, and a pressure drop ratio of 1.05. Ideal gas behavior and constant specific heat were assumed for the air. The turbine inlet temperature was assumed to equal the maximum receiver cavity temperature.

In the two window receiver, the active window cooling process has an important effect on the thermodyamic cycle efficiency. The air is heated as it passes between the windows so that it is at a higher temperature when it enters the regenerator. Thus the use of the window reduces the amount of heat that can be removed from the exhaust stream. This has the effect of significantly reducing the overall system efficiency. A second effect of the active window cooling process is to cause an increase in the pressure drop between the compressor and the turbine. Calculations of this pressure drop for typical window configurations show that this effect is very small.

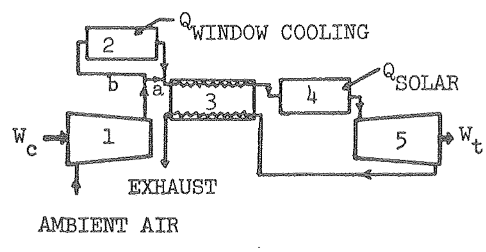

Figure 1. Thermodynamic cycle, where 1 is the compressor, 2, is the inter-window cooling space, 3 is the regenerator, 4 is the receiver, and 5 is the turbine.

7. RESULTS AND DISCUSSION

7.1 Baseline Design

Tables I and II contain the baseline values and results for the one window analysis. The single window receiver efficiency is 93.8

percent and the glass temperature is 1070°K. Table II contains a breakdown of the window heating loads, cooling loads, and receiver energy losses. Over 80 percent of the window heating load is due to the absorption of cavity radiation. Radiative emission by the window accounts for over 90 percent of the window cooling. Table III contains the baseline values and results for the two window analysis. Reference 2 contains a tabulated breakdown of window heating and cooling loads, and receiver energy losses for the two window receiver.

Table II
Heat fluxes - One window system

Heat Flux	Value w/m^2	% of cooling	% of heating	% of loss
$q_{s,a}$	2.20×10^4		17.3	
$q_{p,a}$	1.03×10^5		81.0	
$q_{c,i}$	2.21×10^3		1.7	
q_e	5.91×10^4	92.9		47.7
$q_{c,o}$	8.98×10^3	7.1		7.2
$q_{p,t}$	4.59×10^4			37.0
q_{ref}	1.00×10^4			8.1

*The subscripts are defined as follows: s, solar; o, outer window; i, inner window; t, transmitted; c, convected; a, absorbed; e, emitted; r, reflected; p, cavity.

Table III
Base line results - Two window system*

Quantity	Name	Value
τ_s	Transmittance	0.984
$(\tau\alpha)_s$	Effective $\tau\alpha$	0.0078
T_c	Cav. Temp.	1273°K
$\alpha(T_c)$	IR Absorp.	.685
$\tau(T_c)$	IR Trans.	0.305
$(\tau\alpha)(T_c)$	Effec. IR Trans.	.069
$t_{1,2}(T_c)$	Effec. IR Trans.	0.250
$h_{c,i}$	Conv. Coef.	11.0 w/m^2 °K
$h_{c,o}$	Conv. Coef.	11.0 w/m^2 °K
$h_{c,1}$	Conv. Cool Coef.	86.3 w/m^2 °K
$h_{c,2}$	Conv. Cool Coef.	93.6 w/m^2 °K
T_2	Wind. 2 Temp.	773°K
$\epsilon_2(T_2)$	Wind. 2 Emis.	0.926
T_1	Wind. 1 Temp.	996°K
$\epsilon(T_1)$	Wind. 1 Emis.	0.812
η_D	Efficiency	0.954

The active window cooling process reduces the loss due to radiative emission by the window. Therefore, in the two window receiver the transmission of cavity radiation through the windows becomes the largest energy loss. The outer window only reduces the transmission of cavity radiation through the window system by about 5 percent.

7.2 Sensitivity Analysis

In the sensitivity analysis, one system parameter was varied at a time with all other system parameters set equal to the baseline values. Parameters varied include cavity temperature, solar flux, solar absorbance of the window, window reflectivity, and inner and outer convective heat transfer coefficients, window thickness and composition. Only some of these results are presented here.

Figure 2 is a plot of receiver efficiency and glass temperature verses cavity temperature for both the single (S) and double (D) window receivers. In this and in the following figures, the subscripts 1 and 2 refer to the inner and outer window respectively of the double window design. In both systems the receiver efficiency decreases with an increase in cavity temperature, but in the two window receiver the effect is less dramatic. In the one window receiver, the glass temperature exceeds the recommended continuous value when the cavity temperature is raised above 1440°K.

Figure 3 illustrates the effect of incident solar intensity on receiver efficiency and receiver temperature for both systems. The efficiency increases with incident solar intensity but the curve starts to flatten out at high solar flux levels. Figure 3 illustrates that there may be a point above which the marginal improvement in receiver efficiency may not justify further increases in the concentration of the solar system.

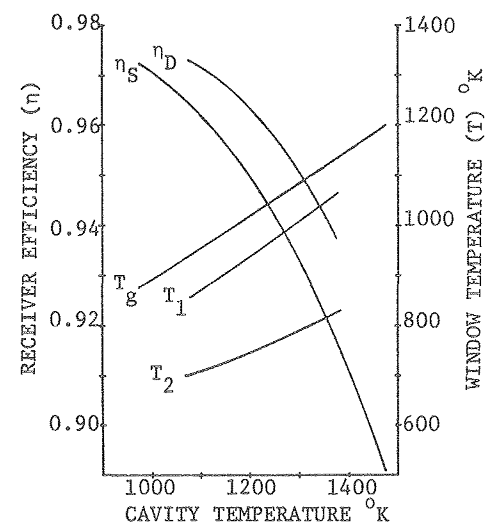

Figure 2. Receiver efficiency and glass temperature vs. cavity temperature.

The glass reflectivity is one of the most important parameters varied in the sensitivity analysis. Figure 4 illustrates the effect of glass reflectivity on receiver efficiency for both systems. For window reflectivity values greater than 2.25 percent (per window) the one window receiver has a higher efficiency.

The thermodynamic cycle efficiency of the two window receiver is significantly lower than that of the one window receiver due to the effect of the regenerator (as discussed earlier). The cycle efficiency increases with cavity temperature while the receiver efficiency decreases with cavity temperature. Therefore, a maximum in the overall efficiency (defined as the product of receiver and thermodynamic cycle efficiencies) is expected at some cavity temperature.

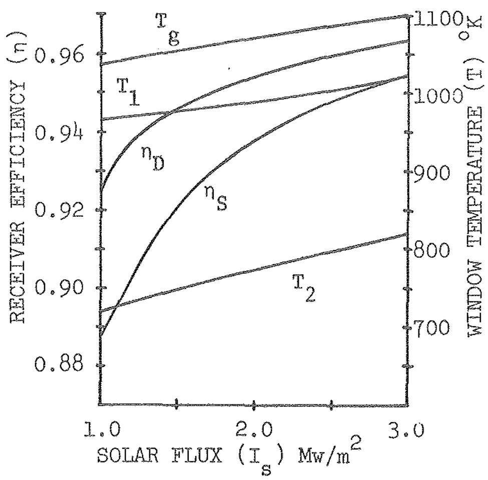

Figure 3. Receiver efficiency and glass temperature vs. incident flux.

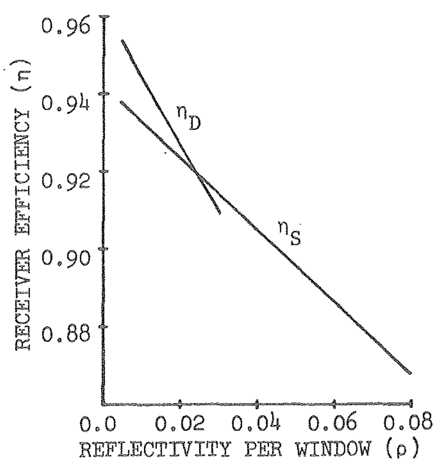

Figure 4. Effect of glass reflectivity on receiver efficiency.

Figure 5 contains a plot of thermodynamic cycle and overall efficiencies. For the one window receiver, the window temperature becomes unacceptably high before the peak in overall efficiency occurs. Due to the poor thermodynamic cycle performance in the two window receiver system, the one window receiver appears more attractive for power production.

8. CONCLUSIONS

An analytical model was developed to predict the receiver efficiency for both single and double windowed, high temperature, solar receivers. A sensitivity analysis was performed to illustrate the effects of changes to system parameters. The parameters that have a large effect on receiver efficiency are the incident solar intensity, the cavity temperature, and the optical properties of the window.

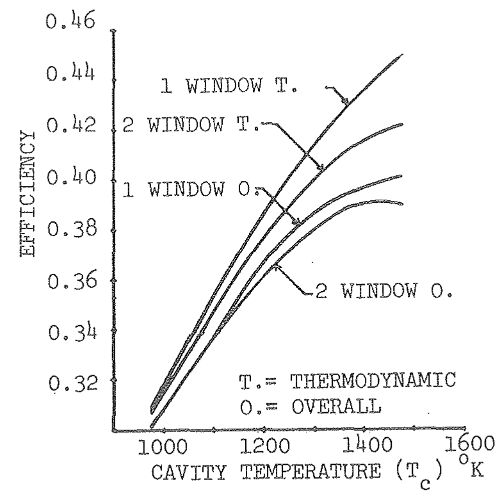

Figure 5. Thermodynamic cycle efficiency and overall efficiency vs. cavity temperature.

9. REFERENCES

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